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Trends in the length of the Southern Ocean sea-ice season, 1979–99

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ABSTRACT. Satellite passive-microwave data have been used to calculate and map the length of the sea-ice season throughout the Southern Ocean for each year 1979–99. Mapping the slopes of the lines of linear least-squares fit through the 21 years of resulting season-length data reveals a detailed pattern of trends in the length of the sea-ice season around the Antarctic continent. Specifically, most of the Ross Sea ice cover has, on average over the 21 years, undergone a lengthening of the sea-ice season, whereas most of the Amundsen Sea ice cover and almost the entire Bellingshausen Sea ice cover have undergone a shortening of the sea-ice season. Results for the Weddell Sea are mixed, with the northwestern portion of the sea having experienced a shortening of the sea-ice season but a substantial area in the south-central portion of the sea having experienced a lengthening of the ice season. Overall, the area of the Southern Ocean experiencing a lengthening of the sea-ice season by at least 1 day per year over the period 1979–99 is 5.6×10^6 km^2, whereas the area experiencing a shortening of the sea-ice season by at least 1 day per year is 46% less than that, at 3.0×10^6 km^2.

INTRODUCTION

The Southern Ocean (Fig. 1) sea-ice cover extends over a vast area, approximately 18×10^6 km^2, in the austral winter and experiences an enormous annual decay each spring and summer, with its coverage at the summer minimum typically reduced to $<4 \times 10^6$ km^2 (Zwally and others, in press). The ice cover has a substantial impact on regional climate, most prominently by restricting exchanges of heat, mass and momentum between the ocean and the atmosphere and by reflecting most of the solar radiation incident on it. It also has a substantial impact on the biology of the Southern Ocean, for instance housing many species of micro-organisms, serving as a platform for penguins, seals and other animals, insulating marine life below the ice from the atmosphere, and reducing light penetration into the ocean. The reader is referred to Bentley (1984), Drewry and others (1993) and Worby and others (1996) for more on the climatological impacts of the ice and to Massom (1988), Drewry and others (1993) and Smith and others (1995) for more on the biological impacts of the ice, including the impacts on primary productivity, phytoplankton blooms, krill and breeding success in seabirds.

Until the 1970s, datasets regarding the Southern Ocean sea-ice cover tended to be sparse both temporally and spatially, due in large part to the vast area, the remoteness from most human habitations and the harshness of the in situ conditions. Fortunately, the ease of obtaining data on the ice cover changed dramatically with the advent of satellite technology. Satellite passive-microwave instrumentation in particular has allowed fairly routine monitoring of the Southern Ocean sea-ice cover since the late 1970s. In fact, the ease with which ice and water can be distinguished in passive-microwave data, due to the sharp contrast in ice and water emissivities at many microwave wavelengths, makes sea-ice coverage now amongst the most readily observed of all climate variables.

This paper takes advantage of satellite passive-microwave datasets over the 21 year period 1979–99 to report on changes in the length of the sea-ice season, defined as the number of days per year with sea-ice coverage, throughout

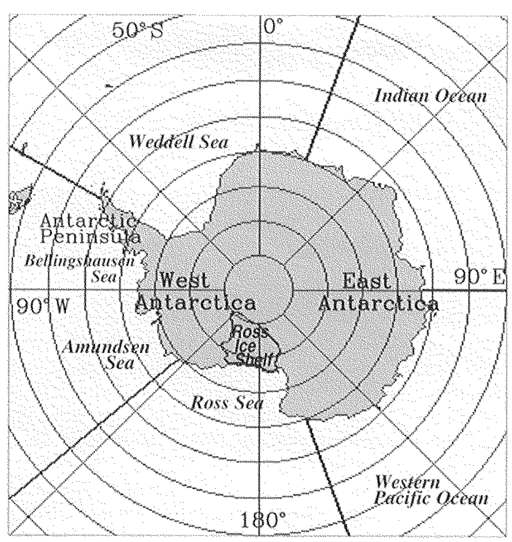

Fig. 1. Location map, including the boundaries of the five sectors into which the Southern Ocean is divided for analysis. The non-land boundaries are along the longitude lines at 20° E, 90° E, 160° E, 130° W and 60° W.

the Southern Ocean. Changes in the length of the sea-ice season not only affect the regional climate and ecology, in ways alluded to above, but also can serve as indicators of change within the broader climate system. The length of the sea-ice season was first examined and mapped for the Southern Ocean in Parkinson (1994), where results were presented for the 8 year period 1979–86. It has subsequently been examined for the 7 year period 1988–94 by Parkinson (1998) and for the two 8 year periods 1979–86 and 1989–96 by Watkins and Simmonds (2000).

DATA AND METHODOLOGY

This study uses data from the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) and the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imagers (SSM/Is). The SMMR instrument collected data on an every-other-day basis for most of the period 26 October 1978 to 20 August 1987, and the SSM/Is have collected data on a daily basis for most of the period since 9 July 1987. The two datasets have been used by Cavalieri and others (1999) to create a consistent set of sea-ice concentrations (areal percentages of sea ice) using an algorithm commonly termed the NASA Team algorithm. This algorithm is based on the assumption of three surface types (two ice types plus liquid water), polarization and gradient ratios calculated from three channels of the satellite data, and a weather filter. The algorithm is described in detail in Gloersen and others (1992), and the procedures for matching the SMMR and SSM/I datasets are described in Cavalieri and others (1999). The ice concentrations have spatial resolutions of approximately 55 km and are gridded to a consistent grid with gridcell size approximately 25 × 25 km (NSIDC, 1992).

The sea-ice concentration data are used here to determine the length of the sea-ice season in each year at each gridpoint, by counting the number of days with ice coverage of at least 15%. Alternative ice-concentration cut-offs of 30% and 50% have also been used, with similar patterns resulting irrespective of which cut-off is selected (e.g. next section and Parkinson, 1994). The 15% cut-off is used for the main results in this paper both because it is the standard cut-off used for the ice-extent results from the same dataset (e.g. Zwally and others, in press) and because comparison of the ice concentrations from the NASA Team algorithm with those derived from other algorithms yields a close match in distributions of ice coverage of at least 15% but some substantial differences in distributions of ice of higher concentrations (e.g. Comiso and others, 1997; Hanna, 1999; Markus and Cavalieri, 2000). The 15% results are thus considered the most robust.

The trend in the length of the sea-ice season is calculated at each ocean gridpoint as the slope of the line of linear least-squares fit through the 21 years of season-length data. The calculations are done through matrix manipulations on the 21 annual matrices of the length of the sea-ice season for the 15% ice-concentration cut-off, and are then repeated for the 30% and 50% cut-offs. For the trend calculations, each year's season lengths are linearly scaled to equivalents for a 365 day year.

In order to obtain a measure of statistical significance for the trend results, an estimated standard deviation (σ) of the 21 year trend is calculated at each gridpoint following Taylor (1997). Trends are considered statistically significant when the trend magnitude exceeds 1.96σ, signifying a 95% confidence level that the slope is non-zero. Trends that additionally meet the criterion of exceeding 2.58σ are considered statistically significant at a 99% confidence level (Taylor, 1997).

SUMMARY AND DISCUSSION

Satellite passive-microwave data have been used to determine and map the length of the sea-ice season in each year 1979–99, with results showing (a) season lengths generally decreasing outward from the coast except in regions of coastal polynyas, (b) perennial ice cover consistently in the far-western Weddell Sea and more selectively elsewhere around the continent, and (c) decidedly short ice seasons (for the high latitudes involved) off the Ross Ice Shelf (Fig. 2). Trends in the season lengths over the 1979–99 period show that: (a) most of the Ross Sea underwent a lengthening of the sea-ice season, (b) most of the Amundsen Sea and almost the entire Bellingshausen Sea underwent a shortening of the sea-ice season, (c) the Weddell Sea had a shortening of the sea-ice season in the northwest but a lengthening of the season in a substantial area of the south-central sea, and (d) around much of East Antarctica, the near-coastal region experienced a lengthening of the season, while further from the coast there was a more even mixture of areas experiencing season shortenings and those experiencing season lengthenings (Fig. 3). Integrating spatially, a much larger area of the Southern Ocean experienced an overall lengthening of the sea-ice season over the 21 years 1979–99 than experienced a shortening (Fig. 4).

These results complement results on trends in the Southern Ocean ice extent (defined as the area having sea-ice concentrations of at least 15%) found from the SMMR and SSM/I record. Analyses of the regional and hemispheric ice extents for the 16 year period 1979–94 by Stammerjohn and Smith (1997) and for the 20.2 year period from November 1978 through December 1998 by Zwally and others (in press) reveal positive ice-extent trends for the Weddell Sea, the Western Pacific Ocean, the Ross Sea and the Southern Ocean as a whole and negative ice-extent trends for the Bellingshausen and Amundsen Seas. The mapped results of the trends in the length of the sea-ice season (Fig. 3) provide a far more detailed spatial picture of the 21 year changes in the Southern Ocean than is possible when examining the ice extents, but at the same time, they provide a far less detailed temporal picture. Together, the ice-extent and season-length results show an overall increasing Southern Ocean ice cover, with the Bellingshausen and Amundsen Seas and the far-western and northwestern Weddell Sea showing instead ice-cover decreases. These results are consistent with reports of notable warming over the Antarctic Peninsula from 1978 to 1996 (King and Harangozo, 1998; Skvarca and others, 1998; both studies also include years prior to 1978) and with a tendency for air-temperature anomalies in the peninsula region to be opposite in sign to those predominating over much of the rest of the Antarctic (Rogers, 1983; Stammerjohn and Smith, 1997).

The satellite-derived Southern Ocean sea-ice results, with overall lengthening sea-ice seasons (Figs 3 and 4) and increasing ice extents (Stammerjohn and Smith, 1997; Zwally and others, in press), provide a sharp contrast with the widely publicized overall ice-cover decreases in the Arctic occurring over the same period. Many uncertainties remain, but one certainty is that the ice covers of the two hemispheres have not been fluctuating synchronously over the past two decades.